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Light transmission efficiency of daylight guidance systems: An assessment approach based on simulations and measurements in a sun/sky simulator

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Abstract

New and more advanced guidance systems are nowadays available, allowing bringing natural light into buildings and offering potentials for energy savings associated to well-being for occupants. From a design point of view, the key factor is the knowledge of their photometric performances in terms of global light transmission efficiency, so as to predict the daylight availability in an interior space due to an array of guidance systems (or, the other way around, to predict the number of pipes needed to produce a minimum natural light illuminance according to standard requirement) through known analytical methods such as the lumen method. In spite of this, determining the global light transmission efficiency of advanced guidance systems is a quite complicate matter because of the redirecting optical properties these elements rely on even in the case of simple typologies (for instance, passive domes with micro-prismatic profiles and micro-prismatic or holographic films used as pipe's coating).

This paper presents an approach to characterize photometric performances of tubular daylight guidance systems in terms of light transmission efficiency: the global system efficiency is the result of the product of the efficiencies of the three individual components (collector, pipe and diffuser) and each efficiency is determined as the ratio of the flux emitted through the output window to the flux hitting the input window, accounting for both the beam and the diffuse efficiency. The approach, based on both measurements on physical models and simulations, was applied to different typologies of pipes and passive collectors and the obtained data were used to eventually calculate the global efficiency for the analyzed system.

Keywords: Tubular daylight guidance systems; Light transmission efficiency; Suns/sky simulators; SkyVision

1. Introduction

A large body of knowledge shows a general preference for daylight as a light source in buildings, due to a series of factors related to its fulfillment of human needs, with consequent beneficial effects on human well-being and performance. Beside this, recent growing concerns about conserving energy and environmental protection have stimulated interest in the use of daylight as a substitute for electric lighting. As a result, daylighting design in buildings has become a major design issue, which led to new strategies for a conscious use of daylight. Within this frame, a research field of increasing interest addresses how delivering natural light into rooms that cannot receive adequate daylight from windows alone: this is the case of small internal windowless rooms or underground interiors of inner areas of large spaces that are far away from any window, a typical condition in deep-plan buildings, like hospitals for instance, that have become quite the norm nowadays. Furthermore, the recent development of new high efficient optical materials

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has made possible the ‘daylight guidance technology’ which, through a large number of optical processes, redirects and transports daylight over distance, i.e. into areas of buildings that cannot be lit using conventional glazing. This technology is based on the use of light pipes, that is to say mirror light guides with highly reflective surfaces, equipped with optical devices to collect both skylight and sunlight flux falling on the horizontal upper opening and to forward it downward by multiple inter-reflections onto the diffusing emitting glazing at the bottom of the tube. This diffuser scatters and redistributes transported daylight over the interior space. According to this general principle, different technologies have been developed (and new ones are under development) to enhance light transmission efficiency: actually, it is evident that the transmission performance of guidance systems (in terms of light flux which is globally transmitted through the system) rises when direct sunlight can be collected and redirected downward along the pipe. For this reason, more sophisticated collectors are equipped with heliostats and sun-tracking mirrors to maximize the contribution of direct sunlight. The resulting active systems provide the best performance under clear sky conditions rather than in presence of overcast skies, thus their use is worthwhile in climates were sunny skies are predominant. Taking advantage of this technology, enhanced tubular daylight guidance systems can be obtained, such as the Heliobus (Heliobus, 2011) and Arthelio (Mingozzi et al., 2001) systems. Alternatively, the guidance system can consist of optical fibers: for instance, the Japanese Himawary (Himaway, 2011) or the Swedish Parans (Parans, 2011) systems collect and concentrate sunlight into fibers using tracking Fresnel lenses. Façade mounted systems represent a further possibility to guide daylight into a building: examples of this technology are the Parans system, which can also be installed onto a façade, or anidolic systems, which consist of a light gathering device oriented towards the equator to collect daylight, a horizontal mirrored guide system within a suspended ceiling and an output device located deep in a building (Lynhart and Scartezzini, 2010; Scartezzini and Courret, 2002). Finally, hybrid systems allowing to simultaneously deliver daylight and electric light into buildings through luminaire-like output devices have been recently developed. A comprehensive overview on available passive and active technologies, as well as on hybrid systems, can be found in (Mayhoub and Carter, 2010).

With respect to the number of more complex and sophisticated typologies of guidance systems being offered in the market, the key factor is concerned with having available data to describe their photometric performances in terms of global light transmission efficiency: from the point of view of designers, suitable and as simple as possible tools are needed since the earliest design stage and throughout the design process to predict the daylight availability in an interior space due to an array of guidance systems or, the other way around, to predict the number of pipes needed to produce a minimum natural light illuminance according to standard requirements). Actually determining such properties is not a trivial matter, especially for what concerns the collectors, which have complex optical redirecting systems also in the case of passive domes (as they have micro-prismatic profiles); pipes’ coating as well may nowadays present redirecting properties thanks to micro-prismatic or holographic films which need to be accurately modeled. The same applies to diffusers which rely on optical devices to scatter light over the room. In the appended discussion related to the presentation of their prediction method, Zhang, Muneer and Kubie acknowledge that “for innovative daylighting devices and some of the new designs, especially those that utilize not only skylight but also sunlight, to date, no general method is available to assess their daylighting performance” (Zhang and Muneer, 2002).

As a consequence, manufactures of guidance systems should provide a detailed characterization of light transmission efficiency for a wide range of sun positions and sky conditions, as efficiency performances depend on the presence of the sun in the sky as well as on its position during the day and throughout the year. If photometric data of guidance systems are scarcely available, methods are required to accurately predict the light transmission efficiency of complex guidance systems. In principle, three approaches could be adopted for this purpose: analytical methods, numerical simulations and measurements using real systems, each with different advantages and drawbacks.

As far as analytical methods are concerned, in literature a number of different formulae have been proposed by several authors over the last years, especially for mirror tubular daylight guide systems (TDGS), under both clear sky and overcast sky conditions. The first studies aimed at determining the tube transmission efficiency TTE based on the light flux calculations (Al-Marwaee and Carter, 2006; CIE, 2006; Shao et al., 1997,1998; Swift and Smith, 1995; Zastrow and Wittwer, 1987; Zhang and Muneer, 2000) while afterwards methods to predict interior illuminance delivered by guidance systems were introduced (Bouchet and Fontoynont, 1996; Jenkins and Muneer, 2004; Jenkins et al., 2005; Zhang and Muneer, 2002). Beside this, several studies and experiments based on measurements taken for prototypes of tubes or for installations in real interiors were carried out (Carter, 2002; Oakley et al., 2000; Robertson et al., 2010). Recently, two more detailed analytical methods were published (Mohelnikova, 2009; Kocifaj et al., 2008): the former provides with a theoretical model for tubular light guides with flat glass cover under clear skies with direct solar radiation, while the latter with a physical model for interior illuminance calculation (named HOLIGILM), for vertical cylindrical skylights, based on a ray-tracing between the diffuser of a TDGS and the sky-vault including the sun. In general, analytical methods, including these latest ones, are based on simplified assumptions with regard to collector and pipe light transmission efficiency: the collector is described through the dome visible transmittance value only, independently of how this is influenced by the collector geometrical and optical properties which result in a complex interaction

of redirecting phenomena (reflection and refraction); furthermore, the values of the reflectance of the pipe's interior coating are considered as independent of the angle of incidence. As a result, analytical methods are not accurate to characterize the light transmission efficiency of complex guidance systems which rely on optical redirection components.

In principle, more consistent results can be obtained through numerical simulations, taking advantage of the large amount of rays that recent tools are able to track and of the improved calculation power nowadays available. But even more sophisticated simulation packages still show limits in accurately model the behavior of redirecting materials and geometries. Simulations provide reliable efficiency performance data for mirror pipes and for many typologies of diffusers (Baroncini et al., 2007), but on the other hand inconsistencies are observed for what concerns the collector efficiencies. A more detailed discussion on this topic is reported later in this paper (see Section 2.1).

A different approach to accurately characterize guidance systems' efficiency is based on physical measurements using real components. This gives the advantage of allowing using 1:1 prototypes of a component (such as collectors with prismatic profiles) or real materials (such as mirror or holographic films), applied to scaled pipes, which can be hardly modeled through an analytical or a simulation-based approach. Measurements can be taken positioning the guidance system either under real sky conditions or in laboratories equipped with a sun and a sky simulator. This latter approach allows the repeatability of standard or climate-based sky conditions and thus comparing different typologies of system configurations. On the other hand, it should be stressed out that this measurement-based approach is time-consuming compared to simulations or analytical methods and requires to have available component prototypes from manufactures.

3This paper is aimed at describing a procedure which was used to characterize the light transmission efficiency of some typologies of passive TDGS with redirecting collectors. Specific efficiencies were determined separately for the three components through an appropriate combination of analytical, software and measurement based approaches. For each component, limits and potentials concerned with these approaches are discussed and the approach which was adopted within this research is illustrated in detail. In particular analytical formulae and the software SkyVision (Laouadi, 2004; Laouadi and Arsenault, 2004; SkyVision, 2011) were used to characterize pipe efficiency, while physical measurements were taken for some typologies of collectors and pipes at the Daylighting Lab of the Politecnico di Torino, through a sun and sky scanning simulator facility (Aghemo et al., 2008).

In the following sections, the methods used to determine the single component and the global system efficiency are described in detail, as well as some measurements and simulations which were carried out as application of the developed methodology. The last section deals with the calculation of the light transmission efficiency for a given typology of guidance system used at different sites across Europe.

2. Assessment of tubular daylight guidance systems' performances

Because of different methods and calculation procedures, the International Commission on Illumination CIE established the Technical Committee TC-3-30 which carried out a comprehensive investigation on guidance topics and properties over the decade 1993–2003 and released a conclusive publication which contains a standardized calculation method (CIE, 2006). According to this publication, the system global efficiency for passive zenithal guides, η_{TDGS}, can be determined through the following formulae:

$$\eta_{\mathrm{TDGS}} = \frac{\text{Standard Daylight Transfer Characteristic}}{A_{\mathrm{TDGS}}} = \frac{\mathrm{SDTC}}{A_{\mathrm{TDGS}}} \quad (-) \tag{1}$$

$$\mathrm{SDTC} = \frac{\text{luminous flux leaving the output window}}{\text{illuminance measured at the input window}} = \frac{\Phi_{\mathrm{output}}}{E_{\mathrm{input}}} \quad (\mathrm{m}^2) \tag{2}$$

where A_{TDGS} is the guide cross sectional area (m^2); SDTC has the meaning of the equivalent area of an open-sky aperture that would produce the same amount of daylight, if there were no losses in the system. The terms Φ_{output} and E_{input} should be both measured on 1:1 prototypes, by using an integrating sphere to create a constant luminance (Lambert radiator) or an artificial sky featuring a CIE Overcast Sky luminance distribution. Considering that specialist photometers are needed for this test, able to house large size components, and only a limited number of these exists, it appears that this approach, based on measuring the efficiency for a whole guidance system, is hardly applicable. For this reason, an alternative approach for calculating the global efficiency η_{TDGS} was used for the research described in this paper, based on a combination of simulations, experimental measurements on physical models or on 1:1 prototypes and, for simplest cases, analytical formulae.

Basically, the global tubular daylight guidance system efficiency is determined as the result of the product of the efficiencies of the three individual components: collector ($\eta_{\mathrm{collector}}$), pipe ($\eta_{\mathrm{pipe}}$) and diffuser ($\eta_{\mathrm{diffuser}}$):

$$\eta_{\mathrm{TDGS}(\gamma_s)} = \eta_{\mathrm{collector}(\gamma_s)} \cdot \eta_{\mathrm{pipe}(\gamma_s)} \cdot \eta_{\mathrm{diffuser}(\gamma_s)} \quad (-) \tag{3}$$

The $\eta_{\mathrm{TDGS}}(\gamma_s)$ value is the result of an appropriate combination of the system efficiency relative to the direct sunlight component $\eta_{b,\mathrm{TDGS}}$ and to the diffuse skylight component $\eta_{d,\mathrm{TDGS}}$, according to the equation (Serra and Marco, 2000):

$$\eta_{\mathrm{TDGS}(\gamma_s)} = \frac{E_{b,\mathrm{out}} \cdot \eta_{b,\mathrm{TDGS}(\gamma_s)} + E_{d,\mathrm{out}} \cdot \eta_{d,\mathrm{TDGS}(\gamma_s)}}{E_{g,\mathrm{out}}} \quad (-) \tag{4}$$

where $E_{b,\mathrm{out}}$, $E_{d,\mathrm{out}}$, $E_{g,\mathrm{out}}$ are respectively the direct, diffuse and global external horizontal illuminance due to an obstructed sky (lux). Since the external environmental factors such as sky clarity, sky-diffuse luminance distribution and sun's position change dynamically, the guidance system overall light transmission efficiency also changes continuously. In particular, the term $\eta_{b,\mathrm{TDGS}}$ depends on the sun elevation angle, γ_s for clear sky and intermediate sky conditions, while for overcast skies it can be assumed as independent of the sun position in the sky. As a consequence, the global tubular daylight guidance system efficiency as well is a value depending on the sun elevation angle and a characterization of a daylighting guidance system for different sun elevation angles should be carried out for a given system.

2.1. Collector performances

Collector performances are expressed in terms of efficiency in collecting sunlight and skylight and redirecting it downward; both a beam and a diffuse collector efficiency should be determined separately and then combined together through the following equations:

$$\eta_{b,\mathrm{collector}(\gamma_s)} = \frac{\Phi_{b,\mathrm{with\ collector}(\gamma_s)}}{\Phi_{b,\mathrm{without\ collector}(\gamma_s)}} \quad (-)$$

$$\eta_{d,\mathrm{collector}(\gamma_s)} = \frac{\Phi_{d,\mathrm{with\ collector}(\gamma_s)}}{\Phi_{d,\mathrm{without\ collector}(\gamma_s)}} \quad (-) \tag{5}$$

$$\eta_{\mathrm{collector}(\gamma_s)} = \frac{E_{b,\mathrm{out}} \cdot \eta_{b,\mathrm{collector}(\gamma_s)} + E_{d,\mathrm{out}} \cdot \eta_{d,\mathrm{collector}(\gamma_s)}}{E_{g,\mathrm{out}}} \quad (-) \tag{6}$$

where $\Phi_{b,\mathrm{with\ collector}}$ and $\Phi_{b,\mathrm{without\ collector}}$, $\Phi_{d,\mathrm{with\ collector}}$ and $\Phi_{d,\mathrm{without\ collector}}$ are the luminous flux values (lm) which are measured (or calculated) in correspondence of the output section of a pipe associated to the collector to analyze, with reference respectively to direct sunlight (beam component) and diffuse skylight (diffuse component), with and without the collector.

As far as the collector efficiency calculation is concerned, a substantial lack of analytical approaches can be observed in literature, as mentioned earlier, due to the difficulties in reproducing through simplified analytical methods the interaction between sun/sky rays and the materials and geometries used to collect light and redirect it downward along the pipe. In principle, this interaction could be successfully reproduced and modeled by means of a simulation based approach, taking advantage of ray-tracing algorithms and of the improved calculation power which are nowadays available, resulting in relatively reduced calculation times. It is important to stress out, though, that even the software Radiance (Ward Larson and Shakespeare, 1998), widely acknowledged as the most accurate simulation tool for daylighting, shows limitations in the capabilities of analyzing sophisticated technologies such as guidance systems. Due to the inherent inaccuracy in tracking light rays through the three component of a guidance system, Radiance users generally adopt a different approach, still yielding acceptable results for many applications: the whole guidance system is replaced by a luminaire applied at the centre of the diffusing component with an associated photometric file which accounts for the efficiency performances of the collector – pipe – diffuser system. This efficiency has to be determined by the user through some approximate calculations or analytical equations existing in literature or through dedicated simulations on simplified components (Ellis et al., 2004; Paroncini et al., 2008). For example, the software SkyVision, developed at the National Research Council of Canada, could be used for this purpose. This allows assessing both beam and diffuse efficiency for some simple passive collector typologies, such as circular domes, square domes and pyramids (square, hexagonal and octagonal). But in general terms, it remains difficult for a simulation tool to accurately reproduce innovative collectors with complex redirecting systems, such as domes with micro-prismatic profiles. For the next future, new simulation possibilities seem to be offered by a recently developed tool called *Photon Mapping* (Schregle, 2005): this is a photometrically validated forward ray-tracing algorithm conceived as a supplementary calculation tool to integrate backward ray-tracing calculations carried out by Radiance so as to more accurately model specular phenomena concerned with transmission, reflection and refraction (hence overcoming the inherent Radiance limits in modeling specularity). Photon map is expected to be soon implemented into the Radiance code and will enable Radiance to efficiently model redirecting systems, including active collectors equipped with sun-tracking systems and specular pipes of daylight guidance systems.

Alternatively, data provided by manufacturers could be used: these are offered as photometric files, but normally they are made available for a limited number of conditions. For instance, they refer to a sun elevation angle of 40° only, which does not describe exhaustively the system behavior in response to external conditions which vary dynamically throughout the year: the efficiency performance can actually vary considerably according to the sun position, in particular with regard to the collector properties. As a result, different sets of data should be provided by manufactures so as to account for different sun positions and sky conditions (clear, intermediate, overcast). In general terms, the behavior of complex fenestration systems relying on optical redirecting systems (including guidance systems) requires a precise knowledge of their directional light transmission features. These photometric properties are described by a Bi-directional Transmission/Reflection Distribution Function (BTRDF), which is experimentally assessed by a bi-directional photogoniometer and which is a data to input in a simulation tool to model materials and geometries (Andersen et al., 2005; Grobe et al., 2010).

As an alternative approach, a sun/sky simulator could be adopted to physically measure light transmission efficiency

of guidance systems, as this kind of facility allows real collectors to be used. On the other hand, measurements are time-consuming compared to simulations or analytical methods and require to have available component prototypes from manufactures; furthermore, results which can be obtained are not in terms of BTRDF. The sun simulator and the sky simulator operating at Politecnico di Torino are used separately: as a consequence, both beam and diffuse collector efficiency values can be measured, through the sun simulator to assess $\eta_{b,\text{collector}(\gamma_s)}$ and through the sky simulator to assess $\eta_{d,\text{collector}(\gamma_s)}$, this latter with reference to both clear and intermediate and overcast sky conditions such as the ones standardized by the Commission Internationale de l'Éclairage (CIE, 2003). As an example of the potentials concerned with this approach, the results of an experimental study are shown: the light transmission efficiency of some collectors was measured in 1:1 prototypes under the sun and sky-scanning simulator facility. The prototypes were passive systems (without any sun-tracking system), provided by the manufacturer (Solatube/Infinity Motion™ (SolaTube, 2011)). They were characterized by different sizes and geometries to redirect sunlight and skylight, consisting of micro-prismatic profiles and presence of an internal reflector. Fig. 1 shows and describes the characteristic and the working principle of two of the collectors which were analyzed: a conventional and an innovative collector with two prismatic profiles, without internal reflector.

For each collector, light efficiency was analyzed by measuring, with and without the collector, the illuminance distribution over the output window of a 0.3 m long mirror pipe associated to the collector to analyze. For this purpose, specific miniaturized illuminancemeters were used, spaced as closely as possible so as to accurately assess the illuminance distribution, which is strongly affected by collector refraction and pipe mirror reflecting properties (Fig. 2). The illuminancemeters were positioned so as to "cover" one third of the reference plane: consequently, for a given sun or sky condition, the collector + pipe system was given a three scan azimuth rotation to cover the overall area of the window output and illuminances were measured for each scan. Eventually the mean value was calculated. The reference plane was coated with a black fabric, so as to minimize as much as possible any occurrence of parasite reflections.

From an operational point of view, to assess the beam collector efficiency $\eta_{b,\text{collector}(\gamma_s)}$ with the sun simulator measurements were repeated eight times, each time tilting the collector with respect to the sun simulator so as to reproduce eight sun elevation angles in the range 5–75°, with an increment step of 10°. In this way, the variation in collector performance as the sun position in the sky varies was taken into account. Considering that the collector presents a geometrical symmetry with respect to a vertical axis, the effect of azimuth rotations to account for different sun's azimuth angles was not modeled.

Because of the finite distance between the stand on which the model/prototype rests and the sun (or the portion of the dome), a parallax error can occur, since different parts of the considered model/prototype receive different quantities of sunlight (or daylight) (Mardaljevic, 2002). The sun simulator used for the measurements is able to generate a beam of parallel rays, this one being the peculiar characteristic of sunlight. As a consequence, a uniform distribution of illuminance values over the stand is generated, which assures that the closely spaced illuminancemeters practically receive the same amount of sunlight: the non-uniformity of illuminance values within a circular area of 15 cm of diameter (that is the area where the collector is positioned) is less than 15% for sun's elevation angles in the range 90° (zenith)–45° and less than 7% for lower sun positions. The error was quantified in terms of standard deviation to mean illuminance value ratio.

As far as the diffuse collector efficiency is concerned, this depends on the sun position in presence of a clear sky condition, while it does not for an overcast sky: for this reason, two sets of measurements were taken with the sky simulator for the two sky conditions, using the CIE Clear Sky and the CIE Overcast Sky. The parallax error occurring for the sky simulator is lower than what observed for the sun simulator: for the CIE Clear Sky, the non-uniformity of illuminance values over the collector is less than 2% for sun's elevation angles in the range 90° (zenith)–45° and less than 3.5% for lower sun positions, while for the CIE Overcast Sky, it is less than 0.5%. Therefore, it can be reasonably assumed that all sensors receive the same quantity of daylight.

With the CIE Clear Sky, eight measurements were taken for the same sun positions which were used to determine the beam collector efficiency, while with the CIE Overcast Sky, a single measurement was carried out. Tables 1 and 2 show the results which were obtained for the different analyses. It can be observed that the innovative collector increases the efficiency in daylight capturing, with respect to a conventional collector, for lower sun elevation angle (up to about 30°) only; out of this range, the efficiency results lower. In presence of overcast sky conditions, the conventional collector performs a better efficiency. As a result, innovative collectors appear to be more suitable for locations and climate conditions for which the sun remains quite low in the sky throughout the year and for which sunny days are predominant.

2.2. Pipe performances

Pipe performances are expressed in terms of efficiency in transporting sunlight and skylight along the pipe; similarly to what defined for the collectors, both a beam and a diffuse pipe efficiency should be determined separately and then combined together through the following formulae:

$$\eta_{b,\text{pipe}(\gamma_s)} = \frac{\Phi_{b,\text{output}(\gamma_s)}}{\Phi_{b,\text{input}(\gamma_s)}} \quad (-)$$

$$\eta_{d,\text{pipe}(\gamma_s)} = \frac{\Phi_{d,\text{output}(\gamma_s)}}{\Phi_{d,\text{input}(\gamma_s)}} \quad (-) \tag{7}$$

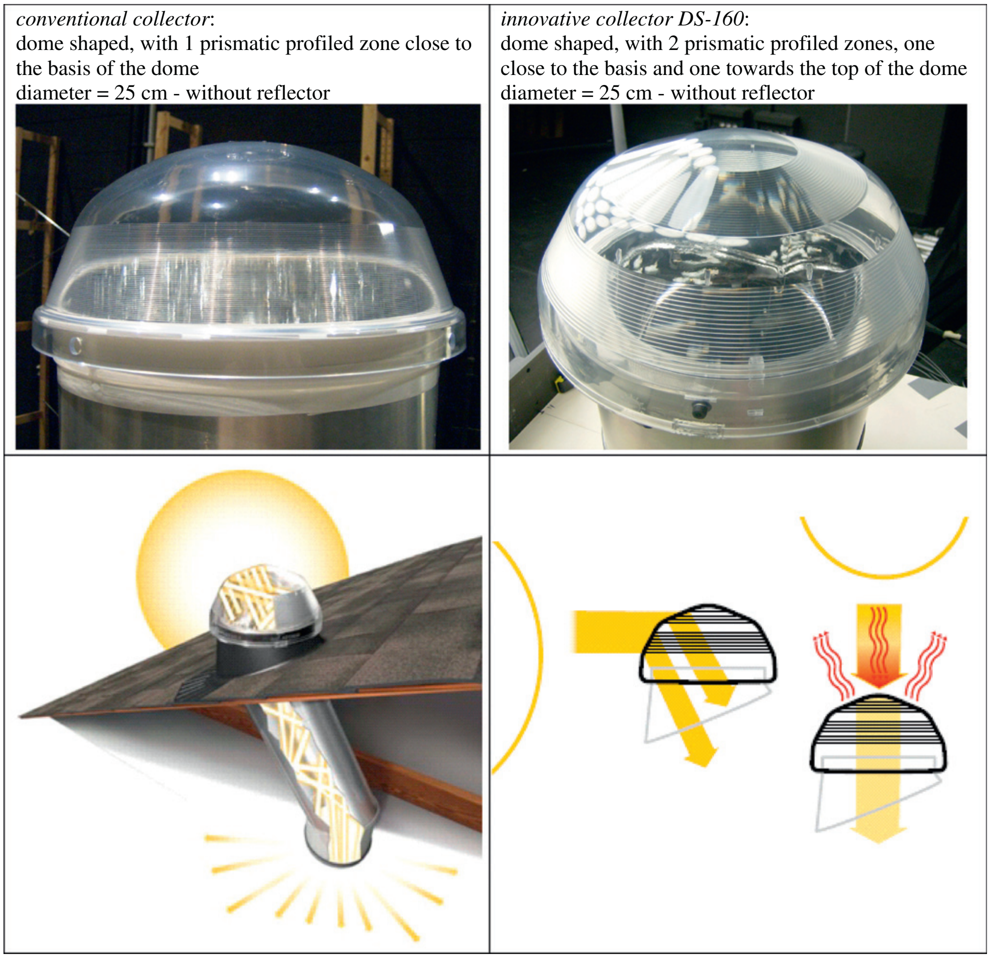


Fig. 1. Characteristics of the Solatube passive collectors which were analyzed in this study. Redirection and reflection of collected sunlight and daylight along the guidance systems is also visualized (courtesy of Infinity Motion – Solatube, 2011).

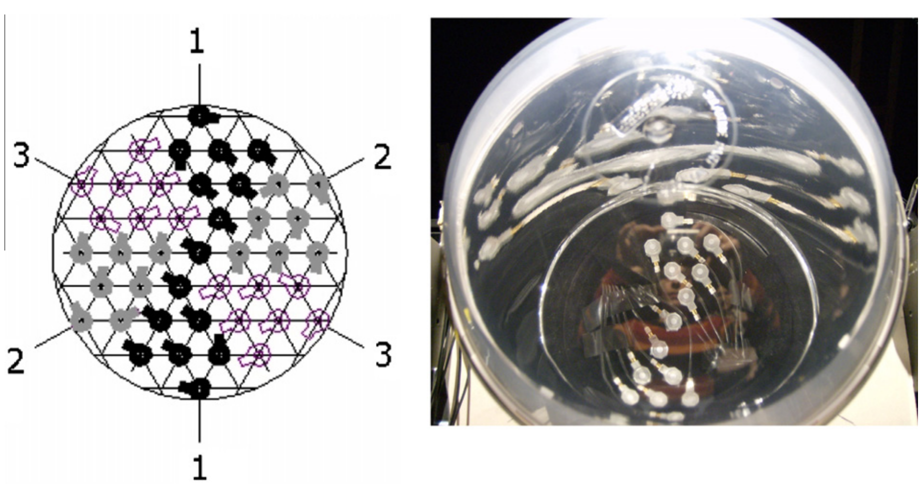


Fig. 2. Positioning of the 15 probes used for illuminance measurement. Only 1/3 of the 25 cm diameter collectors is actually covered, implying respectively a three scan azimuth rotation to cover the overall size of the reference plane.

$$\eta_{\text{pipe}(\gamma_s)} = \frac{E_{b,\text{out}} \cdot \eta_{b,\text{pipe}(\gamma_s)} + E_{d,\text{out}} \cdot \eta_{d,\text{pipe}(\gamma_s)}}{E_{g,\text{out}}} \quad (-) \tag{8}$$

where $\Phi_{b,\text{input}}$ and $\Phi_{d,\text{intput}}$ are respectively the beam and the diffuse luminous flux over the pipe input window (lm) and $\Phi_{b,\text{output}}$ and $\Phi_{d,\text{output}}$ the beam and the diffuse lumi-

Table 1
Efficiency values calculated from measurements taken in the sun simulator for the analyzed collectors with reference to the sunlight direct component $\eta_{b,\mathrm{collector}(\gamma_s)}$.

Collector efficiency values relative to direct sunlight component $\eta_{b,\mathrm{collector},\gamma_s}$ (–)								
	Sun elevation angle							
	5°	15°	25°	35°	45°	55°	65°	75°
Relative difference of innovative collector compared to conventional collector	72.7%	43.5%	23.7%	–5.7%	–14.5%	–19.6%	–28.8%	–27.3%

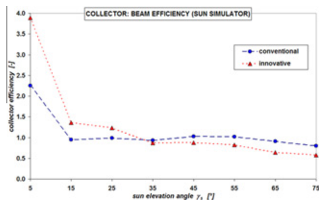
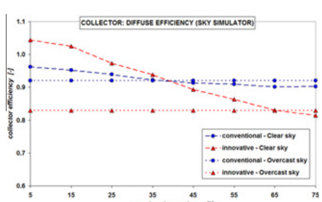


Table 2
Efficiency values calculated from measurements taken in the sky simulator for the analyzed collectors with reference to the skylight diffuse component $\eta_{d,\mathrm{collector}}$. Sky condition used as reference: CIE Clear Sky and CIE Overcast Sky.

Collector efficiency values relative to skylight diffuse component t $\eta_{d,\mathrm{collector},\gamma_s}$ (–)								
CIE Clear Sky								
	Sun elevation angle							
	5°	15°	25°	35°	45°	55°	65°	75°
Relative difference of innovative collector compared to conventional collector	8.4%	7.7%	3.6%	1.7%	–2.2%	–5.1%	–7.9%	–9.8%
Collector efficiency values relative to skylight diffuse component $\eta_{d,collector}$ (–)								
CIE Overcast Sky								
Relative difference of innovative collector compared to conventional collector	–10.2%							



nous flux measured (or calculated) in correspondence of the pipe output window (lm).

Unlike what highlighted for collectors, analytical equations are available in literature for tubular mirror pipes to estimate pipe efficiencies: one is the Zastrow–Wittwer formula for *clear* sky conditions (Zastrow and Wittwer, 1987); the second one is provided by the CIE Publication 173:2006 for *overcast* sky conditions (Al-Marwaee and Carter, 2006; CIE, 2006):

$$\eta_{\mathrm{pipe,clear}(\gamma_s)} = \rho^{L\tan(90^\circ-\gamma_s)/D_{\mathrm{eff}}} \quad (\text{–}) \text{ clear sky conditions} \tag{9}$$

$$\eta_{\mathrm{pipe,overcast}(\gamma_s)} = \frac{e^{\mathrm{AR}\cdot\tan(90^\circ-\gamma_s)\cdot\ln\rho}}{[1-\mathrm{AR}\cdot\tan(90^\circ-\gamma_s)\cdot\ln\rho]^{0.5}} \quad (\text{–}) \text{ overcast sky conditions} \tag{10}$$

where AR = pipe aspect ratio = L/D (–); L = equivalent optical length (m); D = pipe diameter (m); $D_{\mathrm{eff}} = D\pi/4$ for tubular pipes (m); ρ = specular reflectance of the mirrored inner surface of the pipe (–). Although Eq. (10) is given as a function of the sun elevation angle γ_s, "it gives realistic values for overcast sky conditions, assuming a constant value of $\gamma_s = 60°$" (CIE, 2006). As a result, this latter is the approach which was used for overcast sky conditions.

Above formulae provide directly with the global efficiency for a guidance system, without distinguishing between the beam and the diffuse contributions. For a more accurate assessment of beam and diffuse pipe efficiencies, as well as for pipe typologies other than mirror pipes, a simulation program or a scale model based approach should be used. SkyVision, for instance, allows modeling

different material for pipe coating, including user-defined ones. Materials such as mirror films can be reproduced, but limitations still remain as far as materials such as prismatic coatings are concerned. As an alternative, a scale model and sun and sky simulators based approach could be chosen: unlike the case of collectors, for which 1:1 prototypes can be used, a pipe need to be scaled down because of its size, which is not compatible with the size of the sun/sky simulator facilities. On the other hand, it should be noted that real materials can be used, including innovative films currently available to coat the guidance systems to enhance reflecting properties (films with a luminous reflectance as high as 99.5%) or redirecting properties (prismatic or holographic films). Anyway, both approaches, simulations and measurements, allow both beam and diffuse efficiencies to be determined for different sets of clear, intermediate and overcast sky conditions and for different sun positions in the sky.

Among above discussed possibilities, within the study presented in this paper, both analytical formulae, simulations and physical measurements were applied to determine light transmission efficiency of different typologies of pipes. The assessment of pipes' performances was carried out within a more comprehensive study some of the authors recently carried out (Aghemo et al., 2006), where light pipes' transport performances were analyzed both in absolute terms and in terms of natural illuminance values and distribution within a sample underground office). For this purpose, 1:13 scale models of the pipes and of the office were used, as best compromise between a detailed scale and the facility's sizes. Scaled pipes had three different lengths (so as to reproduce 3 m, 6 m and 9 m long pipes), each of which with three different coating: white diffusing painting (used as reference), micro-prismatic film, based on the total internal reflection principle (the Optical Lighting Film OLF™ manufactured by 3M™) and mirror film (the Radiant Mirror Film RMF™ manufactured by 3M™). Real materials were used as coating and their ability to improve the pipe's efficiency was tested by measuring mean illuminance values at the pipe's input and output windows. Output illuminance was assumed as the mean value calculated from 4 illuminance values measured to better account for light distribution inside the pipe. The number of the probes was the maximum possible compatibly with the pipe section (Fig. 3), but it should be stressed out that it could not be enough to accurately quantify the light guided to the end of the pipe, considering that the luminous intensity distribution can have very particular distributions, due to all the redirection/refraction phenomena of light rays.

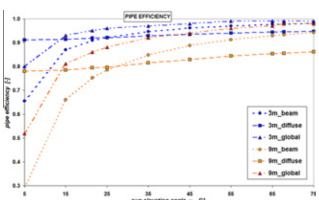
For this reason, both measurements in scaled pipes and numerical simulations were carried out to determine pipe beam and diffuse efficiencies and both were repeated for different sky and sun conditions, which affect the light transport along the pipes and the interaction with the different materials which were used as coating. Numerical simulations were carried out by using SkyVision: the results were used for comparison purposes and to correct efficiency values which were physically measured with the sun/sky simulator facility in the case of longer pipes, i.e. when the parallax error raised up over the acceptable limits. Table 3 summarizes the results which were obtained for the beam and diffuse pipe efficiency through simulations for a clear sky condition, while Table 4 summarizes the results obtained for the diffuse pipe efficiency through physical measurements and simulations for an overcast sky condition. Results obtained for global efficiency as found from Eq. (9) for clear sky and Eq. (10) for overcast sky are also shown for qualitative comparative purposes: in principle, these latter data should actually be comprised between beam and diffuse efficiencies.

From Tables 3 and 4, a quite high relative difference can be observed for both sky conditions between efficiencies obtained through the different approaches which were used. In the case of overcast sky, the analytical approach yields the highest efficiency values, while data obtained from measurements in the sky simulator are the lowest ones. The difference increases as the length of the pipe increases: this is probably due to the simulation error concerned with longer pipes in the sky simulator. Because of the sizes of the stand on which the scaled pipes were places, in the case of 3 m long pipes it was possible to align the input window with the horizon line, while in the case of longer pipes this was not possible. This implied that the

Fig. 3. Positions of illuminancemeters at pipe output window for three pipes with different coating from left to right: 3 M holographic Optical Lighting Film OLF™, 3 M Radiant Mirror Film RMF™ and white painting.

Table 3
Beam, diffuse and global efficiency values of Mirror Light Pipes MLPs from simulations with SkyVision and from analytical formula (9) for different sun elevation angles. The CIE Clear Sky was used, including the direct sun contribution.

L (m)	D (m)	AR (–)	$\rho_{l,\text{coating}}$ (–)	Sun elevation angle									
				5°	15°	21.4°	25°	35°	45°	55°	65°	67.8°	75°
Pipe beam efficiency $\eta_{b,\text{pipe}(\gamma_s)}$ (–) calculated using SkyVision													
3	1	3	0.995	0.64	0.87	0.91	0.92	0.95	0.96	0.97	0.98	0.98	0.98
6	1	6	0.995	0.42	0.75	0.83	0.85	0.89	0.92	0.94	0.95	0.96	0.96
9	1	9	0.995	0.27	0.65	0.75	0.78	0.85	0.87	0.91	0.93	0.93	0.94
Pipe diffuse efficiency $\eta_{d,\text{pipe}(\gamma_s)}$ (–) calculated using SkyVision													
3	1	3	0.995	0.91	0.91	0.92	0.92	0.93	0.93	0.94	0.94	0.95	0.95
6	1	6	0.995	0.84	0.85	0.85	0.85	0.87	0.88	0.89	0.90	0.90	0.90
9	1	9	0.995	0.78	0.79	0.79	0.80	0.82	0.83	0.84	0.85	0.86	0.86
Pipe global efficiency $\eta_{\text{pipe}(\gamma_s)}$ calculated through analytical formula (9)													
3	1	3	0.995	0.80	0.93	0.95	0.96	0.97	0.98	0.99	0.99	0.99	0.99
6	1	6	0.995	0.65	0.87	0.91	0.92	0.95	0.96	0.97	0.98	0.98	0.99
9	1	9	0.995	0.52	0.81	0.86	0.88	0.92	0.94	0.96	0.97	0.98	0.98



sky area close to the horizon was shaded. As a result, the contribution to the light transported along the pipe is reduced to some extent. Anyway, considering the 3 m long pipes only, the difference is still quite significant between the three approaches.

The same applies to the efficiencies obtained for a clear sky condition. The analytical values calculated through formula (9) for the global efficiency are generally higher than both beam and diffuse efficiency data found using SkyVision. From Table 3 it can be observed how beam and diffuse data, calculated using SkyVision, vary according to the sun position: the diffuse efficiency is higher than the beam efficiency for lower sun position in the sky, while for elevation angles over 25° the opposite occurs. Actually, the higher the sun in the sky, the more vertically beam rays enter the pipe through the input window, which result in a higher beam efficiency. On the contrary, for low sun elevation angles, beam rays propagate along the mirror pipe through a high number of reflection, which implies that the beam efficiency value drops. The diffuse efficiency, as expected, is little influenced by the sun position, increasing slowly with the sun elevation angle.

2.3. Diffuser performances

To calculate the overall light transmission efficiency of a TDGS, efficiency performances of the diffuser can be simply taken into account through its luminous transmittance value:

$$\eta_{\text{diffuser}} = \tau_{l,\text{diffuser}} \quad (-) \tag{11}$$

Above formula refer to the quantity of daylight (as a percentage of the daylight falling onto the diffuser) which is globally delivered into the interior space: the directional light transmittance of the diffuser is not taken into account. Especially in the case of diffuser which do not have a Lambert emission, a directional analysis should be carried out, by measuring the light output on real components with the aid of a goniophotometer (Krasnan and Darula, 2009) or through field measurements (Baroncini et al., 2006). The knowledge of the directional transmission of the diffuser, though, is important if the aim is to determine the illuminance within the daylit room, for instance over the working plane. If the aim is to determine the global efficiency of the guidance system, Eq. (11) can be used.

3. Determination of global daylight guidance system efficiency for different sites

As highlighted earlier, once the light transmission efficiencies of individual components have been determined, the global efficiency of a TDGS is eventually calculated through Eq. (3). Beam, diffuse and global horizontal external unobstructed illuminances are used to compute the different component efficiencies as weighted average of the beam and diffuse efficiencies: as a consequence, if the same guidance system is installed in different sites, the resulting average efficiency turns out to be different for the same time of the day or the same date during the year, since both the position of the sun in the sky and the statistical combination of the external

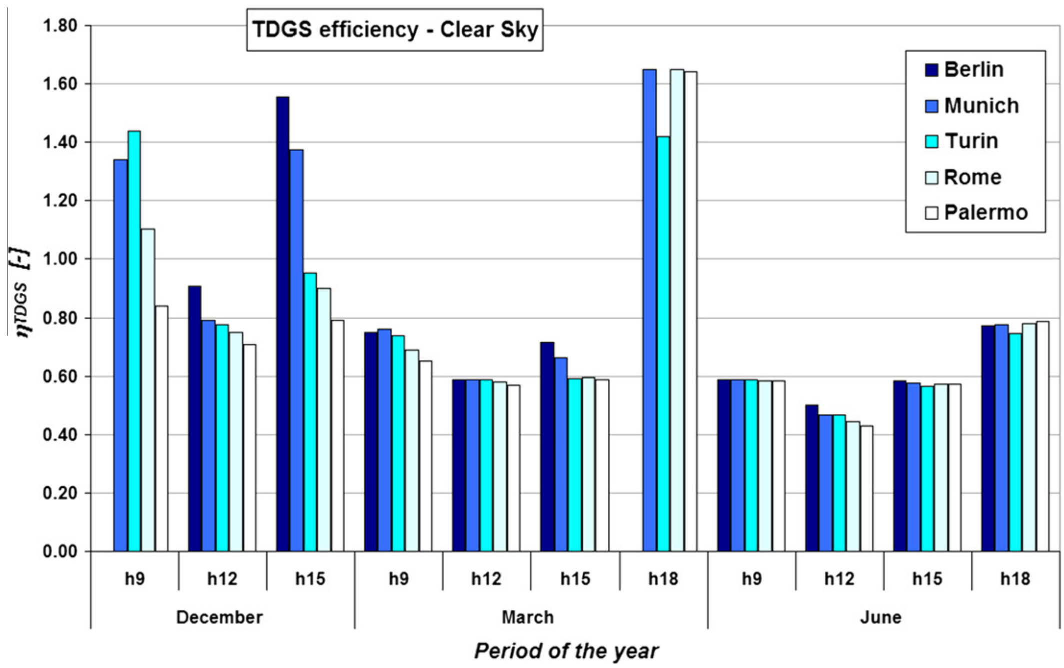


Fig. 4. Global efficiency for a given TDGS for different sites across Europe and for different months throughout the year and hours during a day. The CIE Clear Sky condition is assumed as reference.

beam and diffuse illuminances are different. In this way, the specific climate conditions are taken into account. As an example, Fig. 4 shows the variation of η_{TDGS} values for five sites across Europe for three months throughout the year (December, March and June) and for four different times of the day (9, 12, 15 and, for March and June, 18). The CIE Clear Sky condition was assumed as reference: the external beam and diffuse illuminances to be used to calculate the global TDGS efficiency were derived from the weather files of the considered sites (EnergyPlus, 2011) as average values of illuminances recorded throughout the month (a time-step down to 15 min was assumed for this purpose): only illuminances in presence of clear skies were used for the calculation. The guidance system considered for this example consists of the passive 'innovative" collector described in Section 2.1 and of the 3 m long mirror pipe described in Section 2.2. Beam and diffuse efficiencies were taken from experimental measures for the collector (data shown in Table 1) and from SkyVision simulations for the pipe (data shown in Table 3), while for the diffuser an efficiency of 0.7 was assumed. For intermediate sun elevation angles, a linear interpolation of measured/simulated data was carried out. The figure is quite self-explanatory in showing how strongly the global light transmission efficiency of a TDGS can vary in dependence of the site where the systems is installed and how it is influenced by the sun elevation angle in the sky: highest efficiencies can actually be observed for lowest sun elevation angles, as a consequence of the redirecting action played by the collector micro-prismatic profile.

After having calculated the global light transmission efficiency of a guidance system, the data could be used in a design process to predict illuminance values over a work plane or inside a room resulting from an installations of system or, the other way around, to predict the number of pipes needed to produce a minimum natural light illuminance. Calculation equations based on the lumen method, can be used for this purpose: for example, the CIE publication 173:2006 (CIE, 2006) provides an analytical method, based on the global guide system efficiency and on the utilization factor concept (i.e. the lumen method):

$$\mathrm{DPF}_{\mathrm{wp}} = \frac{E_{\mathrm{wp}}}{E_{g,\mathrm{out}}} = \frac{N \cdot \eta_{\mathrm{TDGS}} \cdot A_{\mathrm{TDGS}} \cdot \mathrm{UF}}{A_{\mathrm{wp}}} \quad (-) \tag{12}$$

$$E_{\mathrm{wp}} = \frac{N \cdot \eta_{\mathrm{TDGS}} \cdot A_{\mathrm{TDGS}} \cdot \mathrm{UF} \cdot E_{g,\mathrm{out}}}{A_{\mathrm{wp}}} \quad (\mathrm{lux}) \tag{13}$$

where DPF = average working plane daylight penetration factor resulting from N daylight guide systems (–), E_{wp} = average working plane illuminance resulting from N daylighting guide systems (lux), N = number of daylighting guide systems TDGS (–), η_{TDGS} = global efficiency of a single TDGS (–), A_{TDGS} = cross-section area of a single tubular daylight guidance system (m^2), UF = utilization factor of a single TDGS (whose values are reported in (CIE, 2006)) (–), A_{wp} = working plane area (m^2), $E_{g,out}$ = global external horizontal unobstructed illuminance (lux).

The daylight penetration factor is "the illuminance received at a point indoor via a light guide from a sky of known or assumed luminance distribution, expressed as a percentage of the global horizontal illuminance outdoor from an unobstructed hemisphere of the same sky. This is analogous to the daylight factor used for conventional windows, with the difference that the *global* external illuminance

Table 4
Diffuse efficiency values for Mirror Light Pipes MLPs from measurements in the sky simulator, from simulations with SkyVision and from analytical formulae for the CIE Overcast Sky condition.

Pipe diffuse efficiency $\eta_{d,\mathrm{pipe}}$ (–)						
L (m)	*D* (m)	AR (–)	$\rho_{l,\mathrm{coating}}$ (–)	Measured in scale model by using the sky simulator	Calculated through simulations (SkyVision)	Calculated through analytical formula (10)
3	1	3	0.995	0.84	0.95	0.97
6	1	6	0.995	0.82	0.91	0.95
9	1	9	0.995	0.73	0.87	0.93

(rather than the diffuse sky component) is used as basis for calculations" (Zhang and Muneer, 2002; CIE, 2006).

Eqs. (12) and (13) can be solved for *N*, thus allowing determining the number of pipes necessary to achieve a minimum natural light illuminance or daylight penetration factor value over a working plane (pipe sizing).

4. Conclusions and discussion

In the frame of the growing interest towards the use of light pipes, which results in beneficial effects on human well-being and performance as well as with potential reduction of the building energy demand of lighting in spaces which would not receive any or suitable daylight, the global efficiency of a tubular daylight guidance systems is the key data to characterize its performance in sunlight and daylight transmission (collection, transport and scatter/redistribution) and hence to proceed to predict natural illuminance values for an installation within a room or the minimum number of TDGS to achieve a threshold illuminance for a given room usage. Performance efficiency of hollow light guides rises when direct sunlight can be redirected downward along the pipe. This puts in evidence the crucial aspect of how to accurately determine the light transmission efficiency of guidance systems with redirecting optical components.

The paper describes an approach which was used to determine the global efficiency of a tubular daylight guidance systems TDGS as the product of the efficiency of each individual component (collector, pipe and diffuser): these can be determined as weighted average of beam and diffuse efficiency of the component, using beam, diffuse and global horizontal external unobstructed illuminances. As a consequence, for the same component, featuring the same beam and diffuse efficiencies, the resulting global efficiency can be different depending on the external conditions, which are specific for the considered site. In this way, the specific climate conditions are taken into account.

Beam and diffuse efficiencies for the three components can be analytically calculated or derived from numerical simulations or physical measurements in scale models or 1:1 prototypes in sun and sky simulator facilities. Analytical methods are not accurate to characterize the light transmission efficiency of complex guidance systems which rely on optical redirection components: their use should therefore be limited to simple typologies of passive systems with mirror pipes and collectors not equipped with prismatic profiles. Numerical simulations as well, despite the large amount of rays that recent tools are able to track, still show limits in accurately model the behavior of redirecting materials and geometries. Their use is suitable to reliably calculate efficiency performances for mirror pipes and for many typologies of diffusers. The development of recent tools such as PhotonMap are expected to strongly enhance simulation capabilities and hence to allow simulating more complex redirecting systems, such as the ones advanced collectors are equipped with. To date, measurements on 1:1 scale components seem to be an appropriate approach: this gives the advantage of allowing using real components in the case of collectors or real material as coating for pipes, which cannot be used in 1:1 scale, but need to be scaled. In the research described in this paper, a combination of simulations (to determine pipe efficiencies) and physical measurements (to determine collector efficiencies) was used to proceed to calculate the global light transmission efficiency of TDGS.

It emerges how the calculation of the global light transmission efficiency is not a trivial task: different approaches (simulations, physical measurements) may be necessary to accurately determine the efficiencies of the single components. This involves a great number of numerical/physical analyses to be carried out. In principle, each daylighting typology requires a specific study to determine its efficiency: all different geometrical (such as pipe length and diameter, shape of the collector, presence or not of deflecting panels or of micro-prismatic profiles) and photometric parameters should be individually investigated. In the majority of cases, especially as far as efficiencies of collectors are concerned, measurement on 1:1 scale components seem to be the most appropriate approach. Within this frame, manufacturers are encouraged to provide with more detailed technical information about light transmission efficiency for guidance systems for different sun elevation angles and sky conditions. Considering that specialist photometers are needed for these tests, able to house large size components, and only a limited number of these exists, manufacturers should cooperate with research centres or photometric laboratories where such facilities are available. For example, the California Energy Commission Public Interest Energy Research (PIER) program sponsored the development of a test method, and the collection of goniometric data on 22 skylight/lightwell configurations under

overcast skies and for each 10° increment in solar elevation for clear skies. The tests resulted in a library of public domain photometric files and photometric reports that can be used by lighting software developers, lighting designers or researchers and others to understand the dynamics of daylight delivered from skylights (McHugh et al., 2002). A similar approach could be fruitfully promoted for guidance systems as well.

Competing interests

None declared.

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